U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL WEATHER SERVICE
1325 East-West Highway
Silver Spring, Maryland 20910-3283

July 15, 1997 W/OH2:DDF

Mr. Douglas Clemetson
U.S. Army Corps of Engineers
Omaha District
215 North 17th Street
Omaha, NE 68102-4978

Dear Mr. Clemetson:

Enclosed is our study on antecedent precipitation requested in Mr. Temeyer's letter of April 24, 1997, and as clarified during subsequent telephone conversations among us. Another copy of this study has been sent to Mr. Richard J. DiBuono, U.S. Army Corps of Engineers, Washington, DC. We trust the study meets with your expectations.

If you have any questions or comments concerning this study, you may reach me at (301) 713-1670 x112.

Sincerely,

Douglas D. Fenn
Meteorologist
Hydrometeorological Design
Studies Center

Enclosure

Precipitation Antecedent to Probable Maximum Storms for the Chatfield, Cherry Creek and Bear Creek Drainages

1. Introduction

This study is a continuation of studies prepared for the U.S. Army Corps of Engineers, Omaha District, in July 1995 (Cherry Creek) and in March and April 1997 (Chatfield and Bear Creek). It was requested in correspondence from the Chief, Hydrologic Engineering Branch, Engineering Division, Corps of Engineers, Omaha, in April 9th of this year.

The study also supplements, to a limited extent, NOAA Technical Memorandum, NWS HYDRO 45--Relationship Between Storm and Antecedent Precipitation Over Kansas, Oklahoma, and Eastern Colorado, January 1995, hereafter referred to as HYDRO 45. Most of the statistical relationships developed for HYDRO 45 were not investigated in the present study due to time constraints.

The objective of this study is limited strictly to determining whether available storm data (sequences of daily precipitation amounts) reveal trends in these amounts (expressed as a percentage of a subsequent central storm--or wet event-amount) as the storms or wet events producing them become increasingly large. The daily precipitation information was handled or manipulated somewhat differently (from HYDRO 45) in this study. One of the more important differences was in the way in which a wet event was defined and another was in our focus on just the precipitation occurring prior to a wet event. So, numerical results from the two studies are not directly comparable, but it should be noted that such direct comparisons were not considered essential for the present study. However, the findings of this study are not at odds with HYDRO 45. The plan of this study is as follows:

A. Define a region within which storms should have meteorologically homogeneous characteristics and which also encompasses the Chatfield, Cherry Creek and Bear Creek drainages.

B. Extract only those daily precipitation amounts from records for such storms in which at least 2.00 inches of precipitation was recorded on one or more days of the storm. In addition, include those recorded daily amounts found up to 15 days prior to the heaviest day of recorded precipitation.

C. Determine the characteristics of the wet and dry periods antecedent to the storms identified in B.

In carrying out the plan, the following definitions were used:

The homogeneous region consisted of eleven contiguous subareas. Plates Vb and Vc--Regional Limits for Terrain Classifications of Hydrometeorological Report 55A were inspected for guidance in limiting the region. The 11 subareas of the region were:

Subarea	Latitude Range (°N)	Longitude Range (°W)
1	35.8 - 36.9	104.6 - 106.5
2	36.9 - 37.5	104.3 - 106.6
3	37.5 - 38.0	104.5 - 106.8
4	38.0 - 38.3	104.5 - 106.6
5	38.3 - 38.9	104.5 - 106.4
6	38.9 - 39.4	104.5 - 106.5
7	39.4 - 39.8	104.7 - 105.9
8	39.8 - 40.4	104.8 - 105.7
9	40.4 - 40.8	105.0 - 106.7
10	40.8 - 41.1	105.0 - 106.9
11	41.1 - 41.4	105.0 - 107.1

These contiguous subareas will be referred to as "our region" from time to time in this study. This area is shown in outline in Figure 1.

Terms derived for and used in this study in a special way and with particular meanings for it are:

A <u>wet day</u> is any day when .05 inch or more of precipitation has been recorded at a specific latitude and longitude (a location) in the study region.

A series of 31 contiguous days at a location containing at least one day on which 2.00 inches or more of precipitation has been recorded is call a <u>sequence</u>.

The day on which the maximum amount of precipitation is recorded in a sequence is called the <u>central day</u>.

A <u>dry day</u> is any day in a sequence that is not a wet day.

A <u>dry period</u> is a contiguous series of dry days.

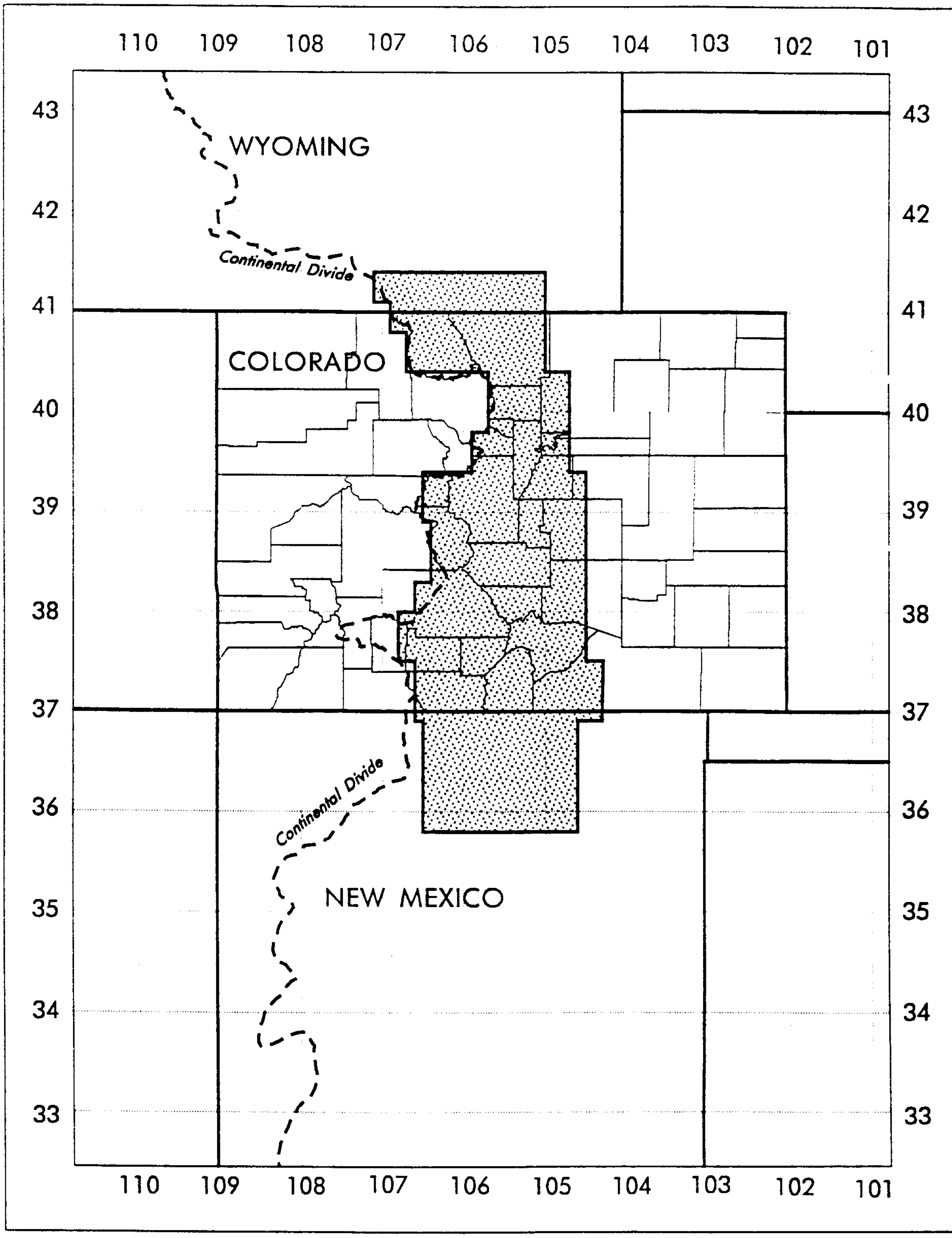

Figure 1. -- The area (shaded) from which precipitation sequences were selected for the study.

A <u>wet event</u> consists of one or more sequences at locations in the study region. The latitudes of all locations must be within 5 degrees of latitude of each other. The central day in each sequence must be within 5 days of the central days of all other sequences.

A <u>wet period</u> is any series of contiguous wet days which contains the central day, but shall be no longer in extent than 5 days. If, in a sequence there are consecutive wet days which immediately precede the wet period, then those days become part of the "antecedent precipitation period" (defined below) for that particular sequence.

A <u>wet period amount</u> is the largest sum of all daily amounts in a wet period at a given location.

The <u>antecedent dry period</u>, if it exists in a sequence, is a series of contiguous dry days which immediately precedes a wet period. There cannot be any wet days between a dry period and the wet period if the dry period is to be regarded as an antecedent dry period. The sum of all daily precipitation amounts in an antecedent dry period must not exceed .09 inches.

The <u>antecedent precipitation period</u> is composed of all the days preceding the antecedent dry period at a location. If there is no antecedent dry period, then the antecedent precipitation period contains all the days preceding the wet period. For this study, the antecedent precipitation period will start or begin no more than 15 days before the central day in a sequence.

<u>Antecedent precipitation</u> and <u>antecedent precipitation amount</u> are the same thing in this report. It/they represent the sum of precipitation amounts during the antecedent precipitation period in a sequence.

For a given wet event having more than one sequence, there will be as many wet period amounts as there are sequences. For this study and in such circumstances, the largest or maximum wet period amount will be used as the denominator when calculating antecedent precipitation to maximum wet event ratios. These ratios will be called <u>antecedent precipitation ratios</u>, or <u>APR's</u>.

The maximum wet period amount for an event is sometimes represented by "XCE." The event itself is sometimes called the <u>central event</u>, and the location at which XCE occurs is sometimes called the <u>central location</u>.

The search through the historical precipitation records identified 720 sequences within the homogeneous region, with a typical period of record for them extending from 1948 to 1994. However, 39 sequences were found prior to 1948, describing 34 separate wet events. The earliest event was in April 1900 and the last one in October 1994. In all, 279 wet events were identified (240 since 1948) from the 720 records or sequences. The revealed characteristics of the 279 wet events in our region will constitute the findings of this study and will be the basis for our recommendations concerning the amount of precipitation and number of dry days likely to precede a probable maximum storm (PMS) for the cited drainages.

2. Findings

The following three sequences describe an event of July 2-3, 1981, as recorded at three locations in Colorado:

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05-8431 37.18 104.52 6050 07/02/81 0 0 0 0 0 0  0 0 0 0  0  3 12 0  0 260 101 1 0 0 0 0 0 0 1 102 20 9 0 7 2
05-8429 37.17 104.48 6030 07/03/81 0 0 0 0 0 0  0 1 0 0  1 22  0 2  1 250  55 0 0 0 0 0 4 1 7  25  0 8 0 8 4
05-8434 37.25 104.33 5750 07/03/81 0 0 0 0 0 0 14 0 0 0 13  8  2 0 15 452   0 0 0 0 0 0 0 0 0   0 48 9 9 0 5
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The leftmost 6 digits identify the state (05 = Colorado) and the location (8429 = Trinidad, 8431 = Trinidad River, 8434 = Trinidad FAA Airport). Following these characters in the sequences are: the latitude and longitudes of the locations, the elevation in feet (Trinidad FAA Airport = 5,750 feet), and the date of the central day. Following the date are 31 daily precipitation amounts, 15 before and 15 after the central day (3 = .03 inches, 260 = 2.6 inches). Note that these data were "extracted" from our historical data files before it was decided that <u>only</u> precipitation amounts <u>before</u> a central event would be relevant. The largest wet period amount in the above example is at the Trinidad FAA Airport and it is summed over two days. This amount, 4.67 inches, will be the wet period amount for the event and will be used as the denominator for the antecedent precipitation ratio (APR). The antecedent dry period is of 2 days extent (the 2 and 0 immediately preceding the 15 and 452). It is not of greater extent because the 8 immediately preceding the 2 represents a wet day, and, thus acts as a bound to this dry period. There are just 3 days providing the entire antecedent precipitation amount of (.14 + .13 + .08) .35 inches. The ratio of antecedent to central event precipitation for this event thus becomes .07, or 7 percent.

Reckonings such as these were made for all 279 events. Four types of comparisons were then made between the (279) APR's and magnitude of maximum wet period amount, number of days in the antecedent dry period, elevation at the location of the maximum wet period amount, and number of days in the wet period.

A. APR Versus Maximum Wet Period Amount (XCE)

Figure 2 is a scatter diagram of these relations. The large capital letters R, S, T, and U are indicators for groups of data points. The significance of these groups will be discussed in a while. It is apparent that the majority of the points have values of XCE less than 5 inches and that for those greater than 5 inches, viturally all are associated with APR's less than .5 or 50 percent. The mean and median values of APR for various intervals of XCE are shown in Table 1. It may be seen that as XCE increases, the associated mean and median APR's decrease. The greater than halving of the mean and median APR's can only be explained partially by the decrease in the average number of days available for antecedent precipitation (see rightmost column) since its variation is smaller than that of the APR's. While admitting that the number of cases supporting the downward trend in APR's is not large, it appears to be based on something more than mere circumstance, and is compatible with Finding #5, found in Section 7, Concluding Remarks, of HYDRO 45, which states, in part, that "The percent of the total antecedent and subsequent precipitation decrease as the central storm amount increases."

Table 1. Averaged values of data displayed in Figure 2 and from the 279 sequences.

Range of XCE (in)	Number of events	Average number of days in wet period	Mean APR	Range of median APR	Average number of days prior to XCE
2 to 3	144	1.8	.37	.25 - .30	14.6
>3 to 4	75	2.9	.28	.20 - .25	14.1
>4 to 5	32	3.3	.27	.15 - .20	14.0
>5	28	3.8	.16	.05 - .10	13.8

To determine if there were groupings or "clusters" of data points in Figure 2, software from Statistical Graphics Corporation, STATGRAPHICS was employed--see Statgraphics Plus Reference Manual, Version 6, Manugistics, Incorporated, Rockville, Maryland, 1992. Results of the software analysis (based on selecting 4 clusters, using the average clustering

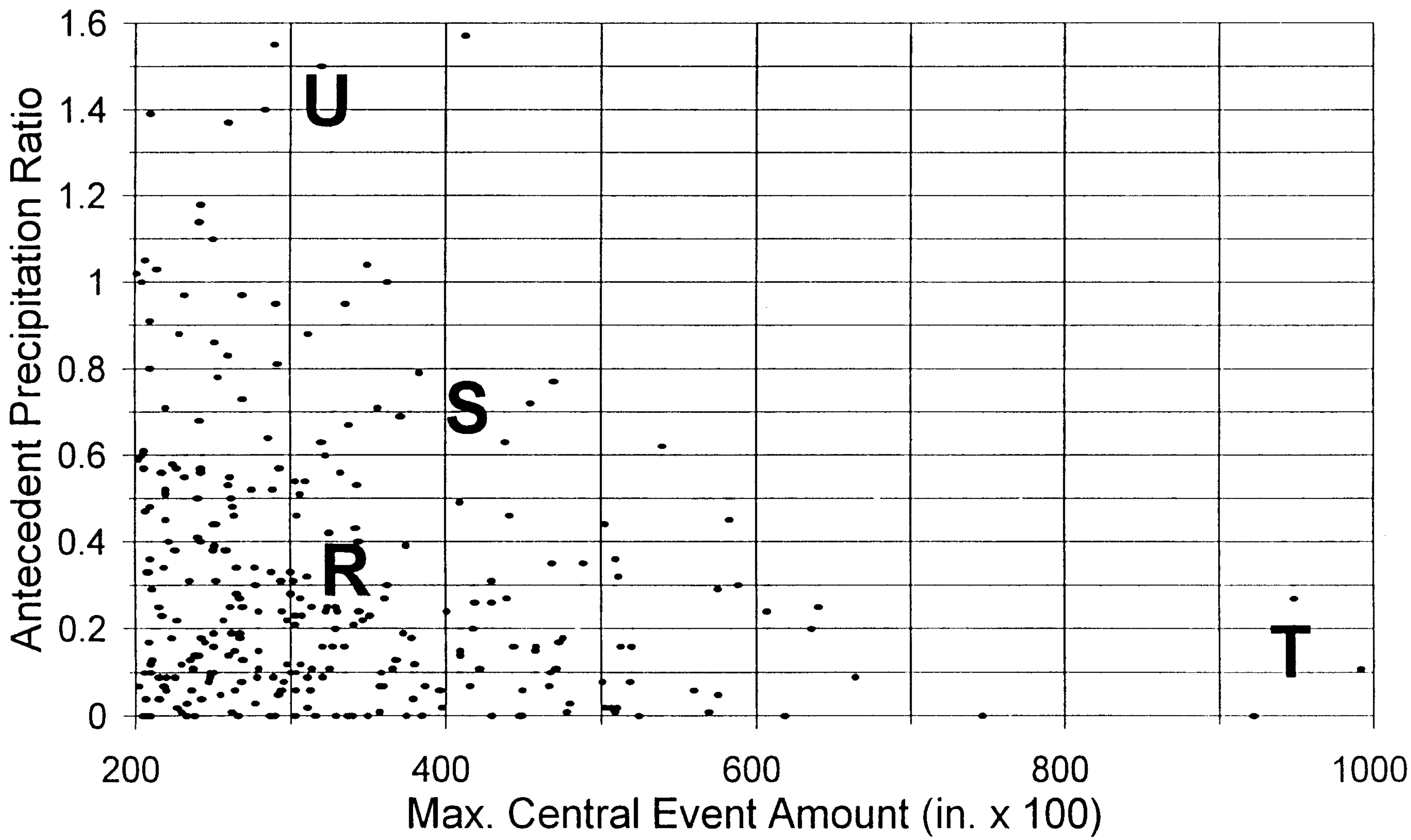

Figure 2. -- Scatter diagram of APR versus maximum wet period amount for 279 events in Colorado, New Mexico, and Wyoming.

method) are depicted in Figure 3. Assignment of points to one of the four clusters is based on spatial relations among the points without reference to their physical significance.

Going back to Figure 2, we can discern four significant groups of points (R, S, T, and U) there because each group represents a unique 15-day storm scenario. Two of these groups (Group U where APR > 1.3 and XCE < 450, and Group T where XCE > 900) are also "picked up" by STATGRAPHICS, but Group U was decomposed into two separate clusters (represented by letters A and D in Figure 3), while the remainder of Group U (the 3 data points near APR = 1.4 and represented by the letter C in Figure 3) were added to what we have termed Group S in Figure 2. This decomposition of six data points into three different clusters was based on spatial considerations, whereas from physical considerations, there should be just one cluster. Group U contains those (6) cases where a relatively low intensity central event is part of a rainy period whose components are not significantly different from one another so that antecedent precipitation ratios are maximized here. The drawn boundaries for Clusters A and D in Figure 3 should not be interpreted as the likely physical limits to those cases where in our region central events are constrained to become insignificantly different from those precipitation periods which preceded them.

Group T in Figure 2 and Cluster B in Figure 3 contain the (3) events of largest XCE in conjunction with antecedent precipitation at or near its minimum. Physically, there is no reason to separate this group/cluster from Cluster C in Figure 3 or Group S in Figure 2. Group T or Cluster B is part of a "natural" progression of increasingly large central events. It just so happens that in our records, there are not enough cases of XCE's between 7 and 9 inches to make this more obvious.

Cluster C in Figure 3 is believed to be composed of two groups, R and S in Figure 2. Group R is defined by .5 < APR > 0 and 400 < XCE > 200 and Group S is composed of the remainder of sequences, along and to the right of a line starting at APR = 1.3 and XCE = 200, and going to APR = .4 and XCE = 900. Group R isolates those sequences in which there is little relation between antecedent and central event amounts, except one is almost as likely in this domain to have low APR's associated with low XCE's as with high and vice versa. However, Group S seems to be composed of sequences in which the antecedent events are in some way constrained not to "steal the scene" so to speak from the main event. Another way to say this is that part of the "setting-up process" or accumulation of energy necessary to prepare for a storm of record-setting proportions in our region, is a suppression of antecedent storms which would otherwise "bleed-off" the energy buildup. If, indeed, Groups S and T are

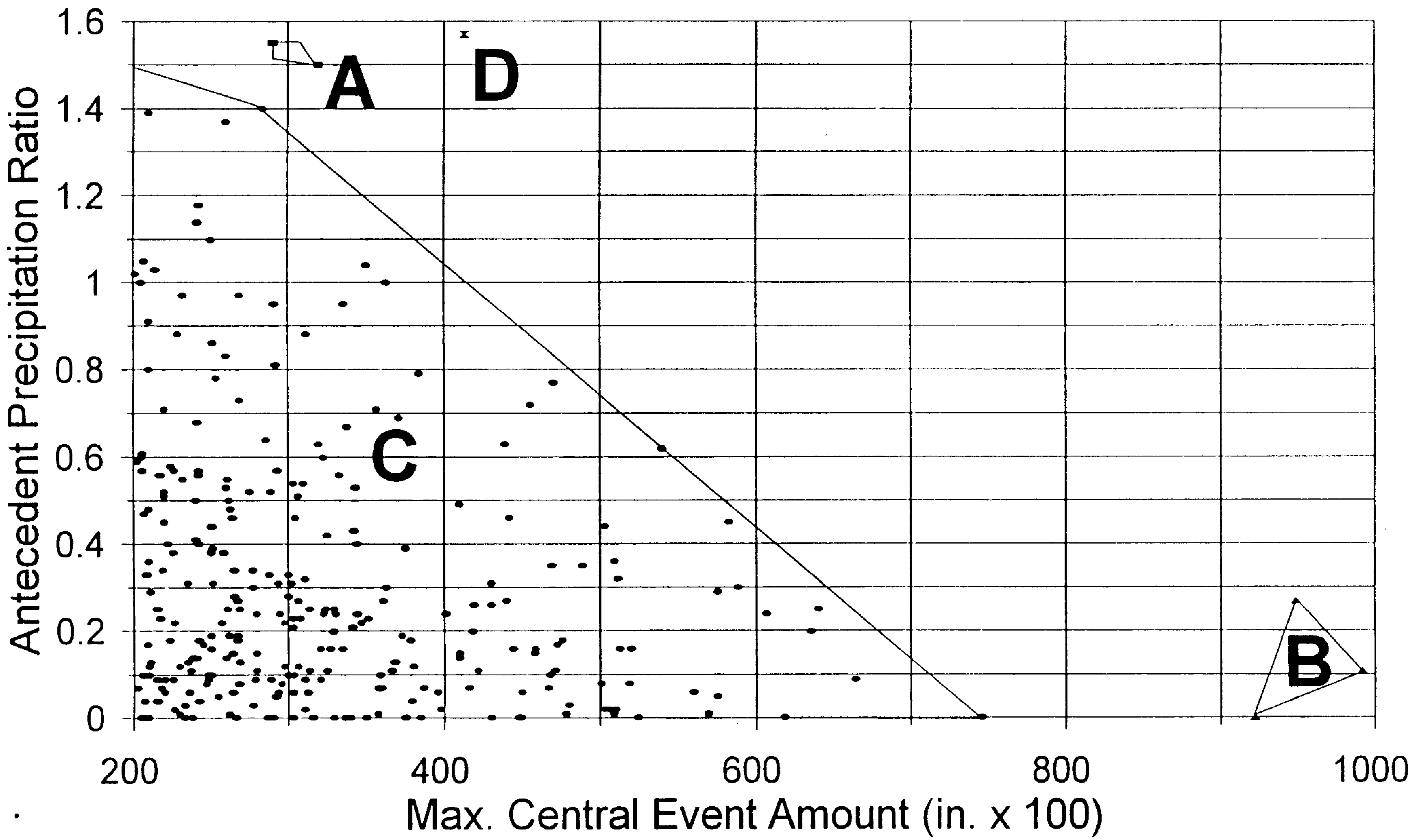

Figure 3. -- Cluster analysis of 279 precipitation events in New Mexico, Colorado, and Wyoming.

parts of a whole, such a "super grouping" supports the notion that as central events become increasingly large (as a consequence of suppression of antecedent precipitation), APR's are likely to level off at some relatively low value, likely below .4 or 40 percent.

B. APR Versus Number of Days in an Antecedent Dry Period

The results of this comparison are seen in Table 2. If an antecedent dry period is anywhere between 0 and 5 days, the APR is near 40 percent on average, but only half that value if the antecedent dry period extends beyond 5 days. On average, the duration of the antecedent dry period has little effect on the magnitude of the central event (XCE) when it is less than 5 days.

Table 2. Averaged APR's related to an antecedent dry period.

Antecedent Dry Period (days)	Average Depth of XCE (in)	Number of Events	Average APR
0-1	3.53	54	.41
2-3	3.14	61	.40
4	3.46	32	.37
5	3.22	21	.40
0-5	3.34	168	.395
>5	3.27	111	.20

C. APR Versus Elevation Range

Table 3 indicates a possible inverse relationship between average APR and magnitude of elevation. However, Table 1 indicated that the larger the XCE for <u>a given event</u>, the smaller the APR, which the <u>average</u> depths of XCE in Table 3 do not confirm. In addition, Table 2 indicated that the longer the antecedent dry period for <u>a given event</u>, the smaller the APR and this condition is not replicated with the <u>average</u> number of antecedent dry days and elevation. So it appears that these data show that there is not a consistent relationship between elevation and APR.

Table 3. *Relations between elevation range at the location where XCE was determined and several antecedent precipitation parameters.*					
Elevation Range (ft)	Number of Events	Average Depth of XCE (in)	Average Number of Antecedent Dry Days	Maximum APR	Average APR
5,000-6,000	79	3.31	5.7	1.57	.35
6,000-7,000	88	3.31	5.4	1.55	.33
7,000-8,000	70	3.24	5.8	1.10	.28
>8,000	42	3.36	5.0	1.50	.29

D. APR Versus Number of Days in a Wet Period

Unlike the inconsistent relations shown in Table 3, the relations in Table 4 are much more, though not completely, consistent with earlier findings. As average depth in the central event increases, the associated APR's decrease. The slight increase shown in going from a 4-day to 5-day central event may be due to the small number of events found at these durations. If the 4- and 5-day events are treated as a whole, then the direction of the tendency is maintained. This tendency is consistent with those discussed in Paragraph A, above, and shown in Table 1.

Table 4. Relations between APR and the number of days used to set XCE.			
Number of Wet Days in Central Event	Average Depth in Central Event (in)	Average APR	Number of Events
1	2.55	.40	76
2	3.09	.29	87
3	3.45	.30	60
4	4.09	.22	24
5	4.70	.25	32
4 & 5	4.395	.235	56

The analysis reported so far has dealt with events ranging in time from 1 to 15 days, but always at a single location. As in HYDRO 45, the range of the spatial scale for a "location" is conceived to extend up to 100-mi^2. However, the areas of concern in this study range from 236-mi^2 (Bear Creek drainage) up to 3,018-mi^2 for the entire Chatfield drainage. In order to get a sense of what an APR might be for area sizes comparable to those of the drainages of interest, we examine six events which had the following characteristics:

a. Each event was composed of at least 10 sequences exclusive of the sequence which set the XCE for the event; and,

b. The six events had the six largest XCE's from the group determined by a.

The results of the examination are shown in Table 5.

Table 5. Observed and derived properties of important storms in one region.

	At the Central Location			"Total" Storm Area Averages					
Events/Dates	XCE (in)	APR	Number of Antecedent Dry Days	XCE (in)	APR	Number of Antecedent Dry Days	Number of Sequences	Ratio of Total Avg. XCE to Central XCE	Total APR Minus Central APR
1 5/18/55	9.92	.11	7	4.95	.18	6.0	26	.50	.07
2 6/16-18/65	9.49	.27	1	5.62	.48	2.2	18	.59	.21
3 5/6-7/69	9.22	.00	13	6.20	.03	7.9	21	.67	.03
4 6/4/49	5.70	.01	1	4.51	.04	5.6	14	.79	.03
5 4/3/86	5.20	.16	2	3.23	.10	9.0	12	.62	-.06
6 4/2/57	4.59	.16	7	3.16	.11	7.9	19	.69	-.05
Column Number	1	2	3	4	5	6	7	8	9

The sense of "direction taken" by APR's as a function of increasing area size and central event intensity is found in Column 9 of Table 5. As the magnitude of the central event (XCE) increases, antecedent precipitation over an area size larger than that representative of a location at the "most intense" center of the storm, becomes a larger percentage of the average depth over this area during its wet period than is the antecedent precipitation at the central location expressed as a percentage of XCE there. A general sense of the area sizes involved may be obtained from Column 8. Assuming these ratios are somewhat akin to areal reduction factors like those graphed in Figures 11.3 to 11.23 of HMR 55A for the PMS, then, depending on assumptions made concerning the topographic classification for the area covered by events 1-6, the area sizes involved in a 3-day central event could be anywhere from 200-mi^2 to over 5,000-mi^2. It is our (as yet unproven or unsubstantiated) hypothesis that area-averaged APR's should vary directly with storm area size.

Column 2 and 5 are, for the most part, consistent with the tendencies shown in Table 1, i.e., to have the larger values of XCE associated with the lesser values of APR. However, Columns 3 and 6 do not paint as consistent a picture with regard to the association of lower APR's with longer antecedent dry periods as shown in Table 2. In spite of this apparent inconsistency, we do not find enough evidence to the contrary to dismiss the earlier finding (in B above) that when central events have become increasingly large, the antecedent dry period was likely to have been (on average) 5 days or longer.

Finally, since values for the PMS have been provided for all months of the year for the Chatfield and Bear Creek drainages, an annual distribution of APR's should be described. Indications are from Table 2 that as the antecedent dry period expands, the associated APR's become smaller. It is reasonable to believe that this shrinkage is due in part to a decreased number of opportunities to have antecedent wet days. If this is so, then, *if climatological records indicate an increased probability for a* rainy day in <u>this</u> month vis a vis other months, and all else is equal, the APR's for <u>this</u> month should be larger than for the other months. We will use the relative increases and decreases in number of rainy days from month to month as shown in the Climatic Atlas of the United States as guidance in distributing APR's throughout the year. The APR values based on our findings will apply to those months when the "all-season" PMS is most likely for a duration of 72 hours as shown in our earlier studies. The monthly values of PMP at 72 hours for subdrainages 8 and 9, as shown in Table 6 of our study dated April 10, 1997, may be used to set the month (May) when a PMS is most likely for the Cherry Creek drainage.

3. Recommendations

The recommendations that follow are based upon available, historical daily precipitation records and informed, albeit subjective, extension from these familiar records to what is likely to be found before and during a PMS. The Climatic Atlas of the United States, Washington, D.C., 1968 will also be invoked to distribute the extended values throughout the year. As more numerous historical precipitation records become available, and as hydrometeorologists' comprehension of the relations between day-to-day storms and storms operating at the limit of the atmosphere's capacity to produce precipitation expands and sharpens, revisions to these recommendations may become necessary.

A. For that month when the 72-hour PMS is most likely (May) at the three drainages of interest in our region, the precipitation in the up to 15-day period preceding it (expressed as a percentage of the 72-hour PMP averaged over the drainage whose area is indicated in the following chart) may be calculated using the following "base" APR's:

Base APR - May					
Drainage Area (mi^2)	<1 to 100	>100 to 500	>500 to 1000	>1000 to 5000	>5000
APR (percent)	30	32	34	36	40

Find the column heading corresponding to the area size of the selected drainage and read the base APR below it. Multiply the 72-hour average depth for May by this percentage to obtain the antecedent precipitation depth for the selected drainage for May. For months other than the "base" month of May, the following percentages should be added to the base APR to achieve the final APR:

Month	JAN	FEB	MAR	APR	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Percent	10	10	7	3	0	0	0	0	3	5	10

Note that these additional percentages are independent of area size. As an example, the antecedent precipitation depth for March for a drainage of 3,000 mi^2 area would be the product of the 72-hour average depth for this drainage for March multiplied by a percentage of 36 + 7 or 43 percent.

B. The dry period immediately preceding the onset of a 72-hour PMS should consist of the following number of days according to season and area size:

Drainage Area Size (mi^2)	<1 to 100	>100 to 500	>500 to 1000	>1000 to 5000	>5000
Season April-October	>5	>5	>4	>4	>3
November-March	>4	>4	>3	>3	>3

Table 6 below provides examples of antecedent precipitation values for several months and drainage area sizes:

Table 6. Example calculations of precipitation for up to 15 days prior to a 72-hour PMS for selected months and drainages.

Month	Drainage	Sub-Drainage	72-Hour PMP (in)	Antecedent Precipitation	
				As Percent	Amount (in)
March	Chatfield	8, 9	23.31	39	9.09
		3a, 4, 5, 6,	16.61	39	6.48
		1, 2, 3a, 3b, 4, 5, 6, 7a, 8, 9	15.30	43	6.58
		Entire	11.83	43	5.09
	Bear Creek	Entire	22.65	39	8.83
May	Cherry Creek	Entire	24.70	32	7.90
	Chatfield	8, 9	29.36	32	9.40
		3a, 4, 5, 6,	21.20	32	6.78
		1, 2, 3a, 3b, 4, 5, 6, 7a, 8, 9	19.05	36	6.86
		Entire	14.25	36	5.13
	Bear Creek	Entire	28.47	32	9.11
November	Chatfield	8, 9	23.47	37	8.68
		3a, 4, 5, 6,	16.67	37	6.17
		1, 2, 3a, 3b, 4, 5, 6, 7a, 8, 9	16.42	41	6.73
		Entire	12.21	41	5.01
	Bear Creek	Entire	22.03	37	8.15

4. Acknowledgements

Barbara Turner patiently and skillfully prepared the text and tables of the study while Edward Zurndorfer accomplished the cluster analysis of Figure 3. Julie Daniel and Tania Davila prepared Figures 2 and 3 and summer intern Will Leverenz assisted in the preparation of Figure 1.